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DYNAMIC INFORMATION COLLECTION AND FUSION

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Final Report

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The project is aimed at developing a comprehensive framework for control of information collection, fusion, and inference from diverse modalities Our research has been organized under three inter-related thrusts. The first thrust addresses system modeling and local information processing. The second thrust emphasizes the interaction between information and control at different abstraction levels. The third thrust is focused on decentralized processing and interactive fusion. Within Thrust 1, we focused on exploring, developing, and utilizing mathematical models for hard and soft observations, the physical and abstract information states, and the sensing state for local information processing and inference. Within Thrust 2, we have obtained a number of results on sensor scheduling for target tracking, controlled sequential multihypothesis testing, controlled sensing for graph classification, universal outlier hypothesis testing, and optimal search and stop. Within Thrust 3, we have obtained a number of results on interactive fusion, data reduction with quantization constraints, network consensus and quantized alternate direction method of mutlipliers (ADMM), and resource management in sensor networks.

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Final Report

Project Title: Dynamic Information Collection and Fusion

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1 Executive Summary

The project is aimed at developing a comprehensive framework for control of information collection, fusion, and inference from diverse modalities Our research has been organized under three inter-related thrusts. The first thrust addresses system modeling and local information processing. The second thrust emphasizes the interaction between information and control at different abstraction levels. The third thrust is focused on decentralized processing and interactive fusion.

Within Thrust 1, we focused on exploring, developing, and utilizing mathematical models for hard and soft observations, the physical and abstract information states, and the sensing state for local information processing and inference:

- *Sensing-aware inference with high-dimensional signals. [1–9]* Here, motivated by applications involving the control of information collection, we analyzed the fundamental limits of supervised inference in problems where the observations of the state are high-dimensional, indirect, and noisy but the sensing process has an underlying low-dimensional structure which is partially known.

- *Discovering latent patterns in high-dimensional data. [10–19]* Here we studied the problem of modeling and discovering salient latent topics or patterns in soft and hard observations with provable performance guarantees. Applications include higher-level inference tasks such as inferring "intent" and other abstract patterns of behavior from soft data, e.g., twitter feeds, text and email messages, text-based event transcripts, expert assessments, etc. Other applications include mid-level inference tasks, e.g., estimating regions of observed scenery that are "most interesting", i.e., salient, relative to a context of "common-place" imagery in automated visual reconnaissance missions using UAVs. Video saliency estimates can be used to select (control) subsequent sensing states to maximize information collection.

- *Action recognition on the feature-covariance manifold. [20–22]* Here we developed and analyzed sparse linear and nonlinear manifold representations of video signals for detecting and recognizing local activity using low-dimensional empirical feature covariance matrices.

Within Thrust 2, we have obtained the following results on the interaction between information and control in various inference contexts.

- *Sensor Scheduling for Energy-Efficient Target Tracking in Sensor Networks. [23–26]* We studied the problem of tracking an object moving randomly through a network of wireless sensors. Our objective was to devise strategies for scheduling the sensors to optimize the tradeoff between tracking performance and energy consumption.

- *Controlled Sensing for Hypothesis Testing. [27–31]* We considered the problem of multiple hypothesis testing with observation control, and studied the structure of the optimal controller under various asymptotic regimes.

- *Efficient Target Tracking using Mobile Sensors. [32]* We studied a mathematical model for tracking of a moving target by multiple mobile sensors in the partially observable Markov decision process (POMDP) framework. We proposed computationally efficient policies for controlling the mobile sensors, and provided a guarantee on their performance relative to that of the optimal policy

- *Controlled Sensing for Sequential Multihypothesis Testing with Controlled Markovian Observations and Non-Uniform Control Cost. [33,34]* We proposed a new model for controlled sensing for multihypothesis testing and studied it in the sequential setting. This new model, termed controlled Markovian observation model, exhibits a more complicated memory structure in the controlled observations than existing models. In addition, instead of penalizing just the delay until the final decision time as standard sequential hypothesis testing problems, a much more general cost structure is considered which entails accumulating the total control cost with respect to an arbitrary control cost function

- *Controlled Sensing Approach to Graph Classification. [35,36]* We posed the problem of classifying graphs with respect to connectivity via partial observations of nodes as a composite hypothesis testing problem with controlled sensing, and proposed a solution that achieves achieves asymptotically optimal error performance, as the error rate goes to zero.

- *Universal Outlier Hypothesis Testing. [37–41]* Motivated by our previous research on the search problem, we studied the following outlier hypothesis testing problem in a universal setting. We have obtained a number of results on this problem.

- *Universal Sequential Outlier Hypothesis Testing. [42–45]* Here we extended our work on universal outlier hypothesis testing to sequential and quickest detection settings.

- *Universal Tests for Optimal Search and Stop. [46, 47]* We studied the problem of universal search and stop using an adaptive search policy. When the target location is searched, the observation is assumed to be distributed according to the target distribution, otherwise it is distributed according to the absence distribution. We assume that only the absence distribution is known, and the target distribution can be arbitrarily distinct from the absence distribution. We developed a universal test for this problem and established its asymptotic optimality

Within Thrust 3, Decentralized Processing and Interactive Fusion, we have obtained the following results in the context of dynamic information collection and fusion for situational awareness.

- *Interactive Fusion.* We extended the sufficiency principle to decentralized inference and developed a new framework for decentralized data reduction. In particular, it was shown that with each node subject to a quantization constraint, the traditional sufficiency framework needs to be augmented by novel notions of sufficiency such as conditional sufficiency. The guiding principle is to minimize information loss instead of preserve the entire information which is often impossible with quantization.

- *Data Reduction with Quantization Constraint.* For a mutli-sensor tandem system, it was established that interactive fusion will strictly improve the inference performance with dependent observations. With conditional independence between the sensor observations, however, there is not asymptotic performance improvement when the sample size increases.

- *Network Consensus and Quantized ADMM.* Network consensus problems are studied in the context of decentralized optimization framework using alternate direction method of multiplier (ADMM), again with the realistic constraint of quantization at each node within the network. Convergence result was established for the first time for deterministically quantizers along with consensus error bounds. The approach has significant implications in network inference as many decentralized inference problems can be framed as multi-agent optimization problems, including the consensus problem.

- *Resource Management in Sensor Networks.* We have studied sensor and resource management under stringent resource constraint for decentralized inference. These include sensor selection, scheduling, bandwidth and power allocation from the perspectives of sparse learning, information theory, economic equilibria and compressive sensing.
- *Decentralized Inference and Information Fusion.* Assured information fusion has been studied in the context of decentralized inference in the presence of adversaries. Specifically, decentralized detection and estimation in the presence Byzantine nodes have been studied where fundamental performance limits as well as robust decision rule design have been investigated.

2 Thrust 1: Modeling and Information Processing

2.1 Sensing-aware inference with high-dimensional signals

Control of information collection often requires decisions to be made about the state of objects based on few indirect noisy observations of high-dimensional signals, e.g., determining the category of moving objects in SAR signals to determine if one should continue exploring a certain geographical region or change the sensing modality and configuration to get a more accurate identification of the object category. This belongs to the broad family of inference problems where the ambient dimension of the sensed data is very large relative to the number of samples but there exists a latent low dimensional sensing structure that can potentially be leveraged for inference tasks. Conventionally, the sensing process is inverted and a decision rule is built in the reconstructed domain, which requires complete knowledge of the sensing mechanism. Alternatively, a direct data domain decision rule might be constructed, but the constraints imposed by the sensing process are then lost. In this work we explored the behavior of a third path we term "sensing-aware inference." This project has contributed to the development of a rigorous theory as well as a practical algorithmic framework for such challenging problems.

Theoretical results for sensing-aware inference: We considered an abstracted binary supervised classification problem with very high dimensional observations, a sensing configuration involving Gaussian likelihood functions, and limited knowledge of statistical models of noise and object which must be learned from limited training data. We analyzed the impact of different levels of prior knowledge concerning the latent sensing structure on supervised classification performance for various classification strategies when the data dimension scales to infinity faster than the number of samples. In contrast to related studies, here the classification difficulty is held fixed as the data dimension scales. We established several results:

1. We first proved that strategies that are based on a naive estimation of all model elements results in a classification performance which is asymptotically no better than pure guessing. We also proved that sensing-aware, projection-based classification rules attain the Bayes-optimal risk. [5–7].

2. *An impossibility result:* We proved that whenever the number of signal dimensions scales faster than the number of labeled samples at constant classification difficulty, the asymptotic minimax classification error probability of any supervised classification algorithm cannot converge to anything less than that of random guessing [2, 3].

   This basic impossibility result points to the fundamental need for sparsity and generalizes and unifies various special cases. In prior related studies of high-dimensional LDA, either the samples per dimension is held fixed (or goes to infinity), or the classification-difficulty is made to vanish as dimensions increase to infinity, or only certain specialized families of learning rules, e.g., maximum-likelihood plug-in rules, were considered.

3. *Necessity of "structure" for good performance in high-dimensional inference:* We showed that unless there exists some type of underlying sparsity in the latent low-dimensional signal parametric structure (specifically that the parametrization have zero measure with respect to the Haar measure on a certain high-dimensional unit sphere), it is impossible for any supervised learning algorithm to attain a non-trivial (i.e., better than random guessing) asymptotic classification error probability in the regime where the number of signal dimensions scales faster than the number of samples while maintaining constant classification difficulty [2].

Much of the existing work has exploited sparsity to achieve good performance in high-dimensional settings. Our theoretical results prove that sparsity is not only "sufficient" but also necessary.

These findings were validated through various simulations. Additional numerical results for support vector machines and sensitivity to mismatch between true and assumed structure were also generated.

Practical algorithmic framework for sensing-aware inference: We formulated sensing-aware inference as inference based on optimally utilizing partial knowledge of a Markov model which relates observed data to the decision state through a latent unobserved variable [1]. This has contributed to the development of new sensing aware inference tools for classical problems. In particular, we developed a new kernel learning approach to supervised classification. We developed a general framework for optimum kernel design based on exploiting knowledge of the sensing structure. We used our algorithmic framework to develop practical algorithms for optimal sensing-aware classification. We applied the methods to document and image classification tasks.

We uncovered the structure of the Bayes-optimal sensing-aware binary classifier. We showed that the Bayes-optimal classifier with partial knowledge of the Markov structure is a linear (hyperplane) classifier in a functional space defined by the partial knowledge. We connected sensing-aware supervised classification to the vast literature devoted to kernel-methods for supervised classification. We showed that the maximum-margin hyperplane classifier in our new functional representation is equivalent to a kernel-SVM where the kernel is determined by the partial knowledge of the Markov observation model. This result has two significant consequences:

1. It immediately leads to practical algorithms for sensing-aware supervised classification since a kernel-SVM can be efficiently solved via a quadratic program.

2. It provides a principled approach to kernel-design for kernel SVMs by leveraging knowledge of the sensing model in an optimal way. Unlike our optimal sensing-aware kernel, the myriad kernels that have been studied and used in the SVM-literature are not designed to directly minimize the classification error. Moreover, those kernels that have been derived from generative models require full model knowledge which is unreasonable for large and complex datasets like text or images.

We showed that the popular bag-of-words model for text and images can be reformulated as a special type of sensing-aware model for inference. We also derived the optimal sensing-aware kernel for this model in closed form and developed several practical alternatives to the closed-form expression. In classification tasks on real-world document and image datasets, the bag-of-words sensing-aware kernel SVM noticeably improves over both standard and domain-specific handcrafted kernels. It even matches the performance of rather sophisticated state-of-the-art approaches such as those based on deep learning.

We also developed an algorithmic framework for designing sensing-aware structured random projections for dimensionality reduction for fast nearest-neighbor classification [4]. The role of sensing structure in a related problem of explosives detection using multi-energy x-ray computed tomography was also explored [8, 9].

2.2 Discovering latent patterns in high-dimensional data

2.2.1 Overview

We studied the problem of modeling and discovering salient latent topics or patterns in soft and hard observations with provable performance guarantees. We adopted the non-negative matrix factorization framework in which "documents" are viewed as probabilistic mixtures of "latent topics" which are modeled as distributions over "words". This is the classic "bags of words" paradigm of probabilistic latent semantic analysis which ignores information in the word-ordering as a first order of approximation. This framework can also be applied to videos and images with words corresponding to photometric and spatio-temporal feature-vectors. With this representation, the matrix formed by the column vectors of word-distributions from each document is to be factorized into a topic distribution matrix and a mixing weight matrix.

A number of approaches have been proposed in the literature for non-negative matrix factorization. Most of them need to resort to some type of approximation to the solution of a non-convex optimization problem (e.g., alternating minimization) or resort to heuristics. In contrast to these approaches we have developed a new geometrically-motivated framework for non-negative matrix factorization based on two key insights:

1. *Separability condition:* the distinguishing characteristic of a topic is the existence of certain novel-words that are unique to that topic, i.e., they either do not occur or rarely occur in other topics (relative to their occurrence in the topic).

2. *Identifiability:* Distinct sets of separable topics when combined with distinct patterns of topic-mixing weights across all documents should not generate statistically indistinguishable patterns of word distributions across all documents.

Based on these two insights, we developed an algorithm for topic modeling and discovery that has provable sample-complexity guarantees, performance that is competitive with the current state-of-the art, and is free of heuristics and approximations [17, 18].

Our algorithm leverages the extreme-point geometry of cross-document empirical word-word co-occurrence frequencies. It makes use of data-dependent and random projections to robustly identify and cluster novel words (extreme points) and associated topics. Our key insight here is that the maximum and minimum values of cross-document frequency patterns projected along any direction are associated with novel words. Our sample complexity bounds for topic recovery are state-of-the-art. The computational complexity of our random projection scheme scales linearly with the number of documents and the number of words per document. In several experiments on both synthetic and realworld datasets, our approach appears to significantly outperform competing methods that have provable guarantees. Furthermore, our approach can deal with degenerate cases found in some datasets where the extreme points can lie on a manifold of a dimension that is lower than the number of topics.

2.2.2 Details of key contributions

We established necessary and sufficient conditions for asymptotically consistent detection of novel words and estimation of topics in separable topic models [16]. We proved that the topic separability condition is an inevitable consequence of high dimensionality (large vocabulary size relative to the number of topics) [12]. We developed a novel distributed algorithm for novel word detection and topic matrix estimation whose statistical complexity is of the same order as that of the current state-of-the-art centralized approaches while requiring insignificant communication between the distributed document collections [14]. We leveraged our insights in topic models to develop a new approach to the learning of item-preference behavior in large communities using results of pairwise item comparisons [10, 11, 13]. Finally, we studied a dynamic (sequential) version of novel word discovery within a hyperspectral imaging application context which combines some elements of controlled sensing (thrust 2) with topic modeling [15].

1. **Necessary and Sufficient Conditions for Novel Word Detection and Topic Estimation in Separable Topic Models:** We demonstrated, for the first time, that the affine-independence condition on the topic-mixing weights is a fundamental, algorithm-independent, information-theoretic necessary condition for asymptotically consistent separable topic estimation. We also showed that the affine-independence condition is sufficient for asymptotically consistent topic estimation in separable topic models. We also showed that the stronger simplicial condition is sufficient for asymptotically consistent novel word detection in separable topic models.

   These conditions and other stronger ones that imply them have played a central role in the development (over the last 6 years) of polynomial time algorithms with provable asymptotic consistency and sample complexity guarantees for topic estimation in separable topic models. Of these algorithms, those that relied solely on the simplicial condition were not impractical while the practical ones need stronger conditions.

2. **Inevitability of Separability: Most Large Topic Models are Approximately Separable** We leveraged separability as a key structural condition in topic models to develop asymptotically consistent algorithms with polynomial statistical and computational efficiency guarantees. Empirical estimates of topic matrices for Latent Dirichlet Allocation models are known to be approximately separable. Separability may be a convenient structural property, but it appears, on the surface, to be a rather restrictive condition. We proved, however, that separability is in fact an inevitable consequence of high dimensionality. In particular, we showed that when the columns of the topic matrix are independently sampled from a Dirichlet distribution, the resulting topic matrix will be approximately separable with probability tending to one as the vocabulary size scales to infinity sufficiently faster than the number of topics. This is based on combining concentration of measure results with properties of the Dirichlet distribution and union bounding arguments. Our proof techniques can be extended to other priors for general nonnegative matrices.

3. **Efficient Distributed Topic Modeling with Provable Guarantees:** Topic modeling for large-scale distributed web-collections requires distributed techniques that account for both computational and communication costs. In this work we considered topic modeling under the separability assumption and developed novel computationally efficient methods that provably achieve the statistical performance of the state-of-the-art centralized approaches while requiring insignificant communication between the distributed document collections. We achieve trade-offs between communication and computation without actually transmitting the documents. Our scheme is based on exploiting the geometry of normalized word-word co-occurrence matrix and viewing each row of this matrix as a vector in a high-dimensional space. We relate the solid angle subtended by extreme points of the convex hull of these vectors to topic identities and construct distributed schemes to identify topics.

The algorithm is based on random projections which consistently detects all novel words of all topics using only up to second-order empirical word moments.

4. **A Topic Modeling Approach to Learning Preference-Behavior from Pairwise Comparisons:** The recent explosion of web analytics tools has enabled us to collect an immense amount of partial preferences for large sets of items such as products from Amazon, movies from Netflix, or restaurants from Yelp, from a large and diverse population of users through transactions, clicks, etc. Modeling, learning, and ultimately predicting the preference behavior of users from pairwise comparisons has been extensively studied since the 1927 work of Thurstone. Yet, almost all models to date have been founded on a clustering-perspective in which users are grouped by their preference behavior. We took a fundamentally different decomposition-perspective and proposed a new class of generative models for pairwise comparisons in which user preference behavior can be decomposed into contributions from multiple shared latent "causes" (partial orders) that are prevalent in the population. We showed how the estimation of shared latent partial orders in the new generative model can be formally reduced to the estimation of topics in a statistically equivalent topic modeling problem in which causes correspond to topics and item-pairs to words. We showed that an inevitable consequence of having a relatively small number of shared latent causes in a world of large number of item-pairs is the presence of "novel" item-pairs for each latent cause. We then leveraged recent advances in the topic modeling literature and developed an algorithm based on extreme-point identification of convex polytopes to learn the shared latent partial orders. Our algorithm is provably consistent and comes with polynomial sample and computational complexity guarantees. We demonstrated that our new model is empirically competitive with the current state-of-the-art approaches in predicting preferences on semi-synthetic and real world datasets.

5. **Dynamic Topic Discovery through Sequential Projections:** In order to connect topic modeling and discovery algorithms of this thrust (system modeling and local information processing) with the controlled sensing thrust, we focused on the aerial hyperspectral imaging application in which words correspond to pixels, topics to different species, and documents to wavelengths or frequencies. The universe of all possible species was modeled as a dictionary and each measurement as the selection of one frequency band. The controlled sensing question of how to select the next frequency band so as to optimize the information gain based on previous observations and knowledge of the dictionary was explored.

   Specifically, we proposed an adaptive strategy for controlling the sensing order in order to maximize a suitably normalized solid angle as a robustness measure of the problem geometry. This is based on efficiently identifying pure pixels that are unique to each endmember and exploiting information from a spectral library known in advance though sequential random projections. Simulations on synthetic datasets demonstrated the merits of our scheme in reducing the observation cost.

2.3 Action recognition on the feature-covariance manifold

Algorithms for recognizing human actions in a video sequence are needed for automated aerial surveillance using UAVs. Developing algorithms that are not only accurate but also efficient is challenging due to the complexity of the task and the sheer size of video.

We developed a general framework for compactly representing, quickly comparing, and accurately recognizing actions using empirical covariance matrices of activity features extracted from video sequences [20–22]. With each pixel, we associate a feature vector which provides a localized description of the action. This generates a spatio-temporally dense collection of action feature vectors. The empirical covariance matrix of this feature vector collection provides a low-dimensional representation of the action. For action recognition, we adapted two supervised learning methods namely the classical nearest-neighbor classifier and the recently developed sparse linear approximation classifier to work with labeled training dictionaries of action covariance matrices. Key to this adaptation is the novel idea that classification algorithms that have been developed for vectors can be re-purposed for covariance tensors by using the log-nonlinearity to map the convex cone of covariance matrices to the (tangent) vector space of symmetric matrices.

We tested the approach on two types of action feature vectors; one based on silhouette tunnels of moving objects and the other on optical flow. Action feature vectors of the first type describe the shape of the silhouette tunnel. Action feature vectors of the second type describe various motion characteristics such as velocity, gradient, and divergence. We demonstrated state-of-the-art recognition performance for both types of action feature vectors on the Weizmann, KTH, YouTube, and the low-resolution ICPR-2010 challenge data sets under modest CPU requirements.

We also demonstrated how our approach can be used for sequentially detecting changes in actions in an adaptive, unsupervised manner so as to parse a long video into sub-videos, each containing only a single action class. We used a non-parametric statistical framework to learn the distribution of the nearest-neighbor Riemannian distances between feature covariance matrices of video segments. Then, we used a binary hypothesis test to determine if new video segments include action changes. In synthetic and natural videos, our algorithm detects roughly 98% of action boundaries with roughly 0.2% false alarm rate.

We also investigated how our framework can be adapted to recognize human interactions, which is typically a more challenging problem due to occlusion between moving individuals. We developed an approach based on dividing human interactions into separate sequences, each containing a single individual, and then combining the estimated action likelihoods for each individual sequence.

The excellent performance of the log-covariance-matrix representation combined with sparse-linear approximation classification demonstrated in our work for action recognition should encourage the use of this framework for other local activity detection, localization, and categorization problems.

3 Thrust 2: Interaction Between Information and Control

3.1 Sensor Scheduling for Energy-Efficient Target Tracking in Sensor Networks

In this part of the project, we studied the problem of tracking an object moving randomly through a network of wireless sensors. Our objective was to devise strategies for scheduling the sensors to optimize the tradeoff between tracking performance and energy consumption. We cast the scheduling problem as a partially observable Markov decision process (POMDP), where the control actions correspond to the set of sensors to activate at each time step. Using a bottom-up approach, we considered different sensing, motion and cost models with increasing levels of difficulty. At the first level, the sensing regions of the different sensors do not overlap and the target is only observed within the sensing range of an active sensor. Then, we considered sensors with overlapping sensing range such that the tracking error, and hence the actions of the different sensors, are tightly coupled. Finally, we considered scenarios wherein the target locations and sensors? observations assume values on continuous spaces. Exact solutions are generally intractable even for the simplest models due to the dimensionality of the information and action spaces. Hence, we devised approximate solution techniques, and in some cases derive lower bounds on the optimal tradeoff curves. The generated scheduling policies, albeit suboptimal, often provide close-to-optimal energy-tracking tradeoffs.

The publications that resulted from this work are [23–26].

3.2 Controlled Sensing for Hypothesis Testing

We considered the problem of multiple hypothesis testing with observation control, and studied the structure of the optimal controller under various asymptotic regimes. First, we considered a setup with a fixed sample size, in which the asymptotic quantity of interest is the optimal error exponent under one hypothesis subject to constraints on the probabilities of error under the alternative hypotheses. For the binary hypothesis case, we were able to show that the optimal error exponent corresponds to the maximum Kulback-Leibler (KL) divergence where the maximization is over the choice of controls. We have further shown that a pure stationary control, i.e., one which is fixed and does not depend on specific realizations of past measurements and past controls (open-loop), is asymptotically optimal even among the class of causal control policies. We also derived lower and upper bounds on the optimal error exponent for the multiple hypothesis case.

We next considered a sequential setup wherein the controller can also decide when to stop taking observations. In this case, the objective is to minimize the expected stopping time subject to the constraints of vanishing error probabilities under each hypothesis. We proposed a sequential test for the multiple hypothesis case and showed that it is asymptotically first-order optimal.

The publications that resulted from this work are [27–31].

3.3 Efficient Target Tracking using Mobile Sensors

We studied a mathematical model for tracking of a moving target by multiple mobile sensors in the partially observable Markov decision process (POMDP) framework. We proposed computationally efficient policies for controlling the mobile sensors, and provided a guarantee on their performance relative to that of the optimal policy. Simulation results showed that our proposed policies did perform close to the optimal policy for certain small spatially stationary models in which a mobile sensor can always move as fast as the target [32].

3.4 Controlled Sensing for Sequential Multihypothesis Testing with Controlled Markovian Observations and Non-Uniform Control Cost

We proposed a new model for controlled sensing for multihypothesis testing and studied it in the sequential setting. This new model, termed controlled Markovian observation model, exhibits a more complicated memory structure in the controlled observations than existing models. In addition, instead of penalizing just the delay until the final decision time as standard sequential hypothesis testing problems, a much more general cost structure is considered which entails accumulating the total control cost with respect to an arbitrary control cost function. We proposed an asymptotically optimal test for this new model and showed that it satisfies a strong asymptotic optimality condition formulated in terms of decision making risk. We also showed that the optimal causal control policy for the controlled sensing problem is self-tuning, in the sense of maximizing an inherent "inferential" reward simultaneously under every hypothesis, with the maximal value being the best possible corresponding to the case where true hypothesis is known at the outset. We also proposed another test to meet distinctly predefined constraints on the various decision risks non-asymptotically, while retaining asymptotic optimality.

We proved our results using a combination of tools and principles from both decision theory and stochastic control. Interestingly, although the role of the causal control policy in the controlled sensing problem is merely to facilitate the eventual testing among the hypotheses without any explicit reward structure to gauge how well the different control policies perform, our results show that there is an inherent *inferential* reward structure maximized by the control policy of the asymptotically optimal test for the controlled sensing problem.

These results were published in [33, 34].

3.5 Controlled Sensing Approach to Graph Classification

We posed the problem of classifying graphs with respect to connectivity via partial observations of nodes as a composite hypothesis testing problem with controlled sensing. An observation at a node is a subset of edges incident to the node on the complete graph drawn according to a probability model, which are modeled as conditionally independent given their neighborhoods. Connectivity is measured through average node degree and is classified with respect to a threshold. We derived a simple approximation of the controlled sensing test and simulated it on Erdos-Renyi Model A graphs to characterize error probabilities as a function of expected stopping times. We showed that our test achieves favorable tradeoffs between the classification error and the number of measurements and further outperforms existing approaches, especially at low target error rates. Furthermore, the proposed test achieves asymptotically optimal error performance, as the error rate goes to zero. See [35, 36] for details.

3.6 Universal Outlier Hypothesis Testing

Motivated by our previous research on the search problem, we studied the following outlier hypothesis testing problem in a universal setting. Vector observations are collected each with $M \geq 3$ coordinates, a small subset of which are outlier coordinates. When a coordinate is an outlier, the observations in that coordinate are assumed to be distributed according to an ?outlier? distribution, distinct from the ?typical? distribution governing the observations in all the other coordinates. Nothing is known about the outlier and typical distributions except that they are distinct and have full supports. The goal is to design a universal test to best discern the outlier coordinate(s). For models with exactly one outlier, we proposed a universal test based on the principle of the generalized likelihood test and showed that it is universally exponentially consistent. We derived a single-letter characterization of the error exponent achievable by the test, and showed that the test is asymptotically efficient as the number of coordinates approaches infinity. When the null hypothesis with no outlier is included, we showed that a modification of this test achieves the same error exponent under each non-null hypothesis, and also consistency under the null hypothesis universally. Then, we studied models with more than one outliers in the following settings. For the setting with a known number of distinctly distributed outliers, we proposed a universally exponentially consistent test, and characterized its achievable error exponent. We also characterized the limiting error exponent achieved by the test, and established that it enjoys universally asymptotically exponential consistency. For the setting with an unknown number of identically distributed outliers, we showed that a different test achieves a positive error exponent under each non-null hypothesis, and also consistency under the null hypothesis universally. When the outliers can be distinctly distributed (with their total number being unknown), we showed that a universally exponentially consistent test cannot exist, even when the typical distribution is known and the null hypothesis is excluded.

These results have appeared in the following publications [37–41].

3.7 Universal Sequential Outlier Hypothesis Testing.

We proposed a universal test based on the principles underlying the Multihypothesis Sequential Probability Ratio Test (MSPRT) and the generalized likelihood (GL) test. When only the typical distribution is known, we derived a lower bound for the error exponent achievable by our proposed test. This lower bound shows that this error exponent is larger than the optimal error exponent in the fixed sample size setting when the outlier distribution is also known. We then considered the completely universal setting where neither the typical nor the outlier distribution is known, and established the universally exponential consistency of our test whenever there are three or more hypotheses. In addition, we derived a lower bound for the achievable error exponent applicable when the number of hypotheses is sufficiently large. We also showed that the asymptote of this lower bound (in the number of hypotheses) coincides with the previous lower bound when the typical distribution is known. With an additional null hypothesis with no outlier, we showed that a suitable modification to our proposed test is universally consistent under the null hypothesis while achieving universal exponential consistency under every non-null hypothesis for both the settings. We have also extended these results to the quickest detection setting. See [42–45] for details.

3.8 Universal Tests for Optimal Search and Stop

We studied the problem of universal search and stop using an adaptive search policy. When the target location is searched, the observation is assumed to be distributed according to the target distribution, otherwise it is distributed according to the absence distribution. We assume that only the absence distribution is known, and the target distribution can be arbitrarily distinct from the absence distribution. An adaptive search policy specifies the current search location based on the past observations and past search locations. At the stopping time, the target's location is determined or it is decided that it is missing. The overall goal is to achieve a certain level of accuracy for the final decision using the fewest number of observations. The results in this work should be regarded as a contribution to the long-studied area of search theory, in particular, searching for a stationary target in discrete time and space with a discrete search effort.

Conceptually, a desirable goal of the search at each location should be to determine if the target is there. To this end, a universal sequential test for two hypotheses can be used at each location to collect multiple subsequent observations that will eventually lead to a binary outcome that the target is there or not. To improve reliability for this binary decision at a particular search location, one can use a test that takes more observations at that location. If we insist on using the mentioned sequential binary test at each location as an "inner" test, then it is convenient to select the current search location based on the past binary outcomes of the subsequent binary tests (instead of all the past observational outcomes of all the searches, generally taken multiple times at each of the locations). With this imposition, the search and stop problem can be conceptually reduced to the problem of constructing an "outer" test for the sequential design of such inner experiments. This intuitive decomposition leads to our proposed universal sequential test for search and stop. We showed that when the target is present, the proposed universal test yields a vanishing error probability, and achieves the *optimal* reliability, in terms of a suitable exponent for the error probability, universally for every target distribution. Consequently, the knowledge of the target distribution is only useful for improving reliability for detecting a missing target. We also showed that a multiplicative gain for the search reliability equal to the number of searched locations is achieved by allowing adaptivity in the search. See [46, 47] for details.

4 Thrust 3: Decentralized Processing and Interactive Fusion

4.1 Interactive Fusion

Existing literature in information fusion almost exclusively assumes a static setting in information flow: nodes propagate information on a directed graph (often in the form of a parallel, tandem, or tree network) and no interaction is assumed or allowed between nodes. We have instead taken a more holistic approach on information fusion where node interaction is allowed in that communications may occur in an interactive manner. Note this differs from the traditional study of feedback in tree structure information fusion as we do not limit the number of rounds of interaction and do not restrict it to only between fusion center and peripheral nodes.

We established that [48], with conditional independent observations, while interactive fusion may strictly improve detection performance in the finite sample regime, it has no improvement over the static tandem fusion system for the large sample regime. The optimum error exponent, namely the Kullback-Leibler distance, remains the same for both system. However, with conditionally dependent observations, strict performance improvement in both finite-sample and asymptotic regimes are possible.

The study of interactive fusion is based on a simple but elegant result regarding the optimal decision structure for general inference problems with convex or affine objective functions. This simple result has broader applications to inference problems that are beyond the specific problem of interactive fusion. For example, one can establish that for the general tandem fusion system, communication direction should always be in favor of the sensor with high SNR, i.e., it should serve as the fusion center [49].

This interactive fusion framework can be applied to various different fusion systems. In particular, we have studied the simple scheme of sensor overhearing in a simple parallel fusion system where similar results have been established that contrast the system performance with overhearing to that of independent processing at all peripheral nodes [50].

4.2 Data Reduction with Quantization Constraint

The sufficiency principle acts as a guiding principle for data reduction in statistical inference. A sufficient statistic is a function of the data, chosen so that it 'should summarize the whole of the relevant information supplied by the sample. In decentralized settings, a sufficient statistic defined with respect to local data is referred to as a local sufficient statistic; if a collection of local statistics form a global sufficient statistic, they are said to be globally sufficient. While sufficiency based data reduction ensures no loss of inference performance using the reduced data, communicating a one-dimensional real data may still be infeasible when communication is subject to a finite capacity constraint. A question then arises that *if each node in a decentralized inference system has to summarize its data using a finite number of bits, is it still optimal to implement data reduction using global sufficient statistics prior to quantization*? The answer is unfortunately *no*, and a simple example is given in [51] that shows globally sufficiency does not guarantee optimal data reduction in the presence of finite-bit quantization which leads inevitably to information loss.

On the other hand, it was also established in [51] that with conditionally independent observations, the traditionally definite global sufficient statistic is still optimal in maximizing the information at terminal node (i.e., the fusion center). With the class of conditionally dependent observations, there also exist cases where quantizing local sufficient statistics is structurally optimal. Using a simple two node system as an illustration, when $\mathbf{X}_1$ and $\mathbf{X}_2$ are conditionally dependent and θ is the underlying parameter of inference interest, a hidden variable $\mathbf{W}$ can be introduced to induce the following Markov chains hold

$$\begin{aligned}&\mathbf{X}_1 - \mathbf{W} - \mathbf{X}_2,\\&\theta - \mathbf{W} - (\mathbf{X}_1, \mathbf{X}_2).\end{aligned}$$

Within this hierarchical conditional independence model, first introduced in [52],, if $T_1(\mathbf{X}_1)$ and $T_2(\mathbf{X}_2)$ are local statistics that are sufficient with respect to $\mathbf{W}$, quantizing $T_1(\mathbf{X}_1)$ and $T_2(\mathbf{X}_2)$ at the respective sensor is structurally optimal for the decentralized inference problem. This new framework of decentralized data reduction with quantization constraints has broad applications to numerous inference problems involving networks of sensors and warrants further studies under more general network settings.

4.3 Network Consensus and Quantized ADMM

There have been very limited algorithms for distributed optimization with the quantized communication constraint. Existing quantized algorithms are developed based on the subgradient and only guarantee to reach a neighborhood of the optimal value at a sublinear rate with the error increasing in the size of the network. Recently an ADMM based quantized algorithm, referred to as the quantized consensus ADMM, (QC-ADMM), has been proposed in [53]. It primarily solves the distributed optimization problem of the following form

$$\arg\min_x \sum_{i=1}^{N} f_i(x),$$

where $f_i : \mathbb{R}^M \to \mathbb{R}$ is the local objective function, using only local computation and quantized communication.

The advantage of the proposed algorithm is that, when certain convexity assumptions are satisfied, all $x_{i[Q]}^k$ converge to the same quantization point within $\log_{1+\eta} \Omega$ iterations, where $\eta > 0$ depends on the local objectives and the network topology, and Ω is a polynomial fraction decided by the quantization resolution, the distance between initial and optimal variable values, the local objective functions and the network topology. Furthermore, the consensus error does not depend on the size of the network and is usually smaller than the error of existing quantized algorithms.

While the above algorithm is readily applied to distributed averaging as it is equivalent to a least-squares minimization problem, we notice that the QC-ADMM does not converge uniquely. For locally convergent algorithms, it is well-known that a good starting point usually helps. Based on this fact, [54] proposed a two-stage method which first uses the ADMM with dithered quantization to obtain a good starting point and then employs the QC-ADMM to reach a consensus. Simulations show that the consensus error of this two-stage approach is typically less than one quantization resolution for all connected networks where agents' data can be of arbitrary magnitudes.

4.4 Resource Management in Sensor Networks

With resource constrained sensor networks, sensor management and resource allocation play a crucial role in maximizing the information gathering capability with limited sensing assets. We have studied the following problems along the line of sensor management for situational awareness.

Sparsity-promoting sensor scheduling

We formulated the sensor scheduling problem as a sparsity-aware optimization problem, where the goal to reduce the number of selected sensors is characterized by a sparsity-promoting penalty term in the objective function [55]. The invented sensor scheduling approach has been successfully applied in field estimation and target tracking [56,57]. Furthermore in [58] and [59], to account for the individual power constraint of each sensor, we generalized the sparsity-promoting optimization framework in [55] by introducing a new sparsity-promoting penalty function which avoids successive selections of the same group of sensors.

Optimal sparse sensor collaboration

The problem of sensor collaboration arises by incorporating the process of inter-sensor communication in a classical distributed estimation network. We associated the cost of sensor collaboration with the elementwise sparsity of the collaboration matrix, and the cost of sensor selection with the rowwise sparsity of the collaboration matrix. Based on such associations, we developed a unified optimization framework in [60] that simultaneously optimizes the collaboration topology, power allocation and sensor selection schemes. We showed that there exists an optimal sparse collaboration topology given limited sensor battery power [61,62], and a trade-off between sensor selection and sensor collaboration [60].

Information-driven sensor selection

We derived an equivalent Kalman filter, known as generalized information filter, for sensor selection [63,64]. We showed that under a regularity condition the design of non-myopic (multi-time ahead) sensor selection policy is equivalent to the design of myopic selection policy at every time step. We obtained near-optimal sensor selection schemes by solving convex programs such as linear programs or semidefinite programs. We showed that the proposed sensor selection approach scales gracefully with network size. We also considered the problem of sensor selection with sensing uncertainty [65], where wIth the aid of mutual information and Fisher information, we developed a multiobjective optimization appraoch to strike a balance between the estimation accuracy and energy usage. When the measurement noise is correlated, we derived the closed form of the Fisher information matrix with respect to sensor selection variables [66, 67]. We theoretically showed the effect of noise correlation on the solutions of sensor selection, and proposed both a convex relaxation approach and a greedy algorithm to find these solutions.

Economic equilibria based sensor management

We considered two different economic models, market equilibrium [68] and mechanism design for sensor management [69–71]. We proposed a framework for the mobile sensor scheduling problem in target localization by designing an equilibrium-based two-sided market model. For the myopic target tracking problem in a wireless sensor network containing sensors that are selfish and profit-motivated, we proposed a crowdsourcing based framework by designing an incentive-compatible mechanism for the bandwidth allocation problem.

Compressive sensing based probabilistic sensor management

We developed a probabilistic sensor management scheme based on the concepts developed in compressive sensing [72]. In the proposed scheme where each sensor transmits its observation with a certain probability via a coherent multiple access channel, the observation vector received at the fusion center becomes a compressed version of the original observations. In this framework, the sensor management problem can be cast as the problem of finding the probability of transmission at each node so that a given performance metric is optimized.

4.5 Assured Information Fusion

As with other technical problems for situational awareness, information assurance plays an integral part in ensuring the integrity of information gathering and processing. Within this context, we have studied the following set of problems.

Detection in presence of Byzantines

We have considered the problem of distributed detection in tree topologies in the presence of Byzantines in [73]. The expression for minimum attacking power required by the Byzantines to blind the fusion center (FC) is obtained. More specifically, we show that when more than a certain fraction of individual node decisions are falsified, the decision fusion scheme becomes completely incapable. We obtain closed form expressions for the optimal attacking strategies that minimize the detection error exponent at the FC. We also look at the possible counter-measures from the FCs perspective to protect the network from these Byzantines. We formulate the robust topology design problem as a bi-level program and provide an efficient algorithm to solve it. Similar analysis has been carried out for the problem of distributed Bayesian detection in the presence of Byzantines in the network [74]. We analyze the problem under different attacking scenarios and derive results for different non-asymptotic cases. It is found that existing asymptotics-based results do not hold under several non-asymptotic scenarios. We next model the strategic behavior of the FC and the attacker using game theory and show the existence of Nash Equilibrium [75]. Also, we obtain the optimal attacking strategy from the point of view of a smart adversary to disguise itself from the proposed detection scheme while accomplishing its attack [76].

Estimation in presence of Byzantines

We have considered the problem of target localization [77] and tracking [78] in Wireless Sensor Networks (WSNs) in the presence of malicious sensors. We analyzed the effect of false information from the Byzantines on target state estimation. We analytically obtained the minimum fraction of Byzantines that blinds the fusion center, i.e., that makes the local sensor data useless to the fusion center. We also proposed a dynamic non-identical quantizer design to reduce the effect of Byzantines on tracking performance. Moreover, for the localization problem with non-ideal channels, we have proposed the use of soft-decision decoding to compensate for the loss due to the presence of fading channels between the local sensors and the FC.

4.6 Other Related Work for Decentralized Inference and Information Fusion

Quantizer Design for Distributed Bayesian Estimation

We considered the problem of quantizer design for distributed estimation under the Bayesian criterion [79, 80]. We showed that for conditionally unbiased efficient estimators, when all the sensors have the same number of decision regions, identical quantizers are optimal. Considering a communication rate constraint on the network, we derived the conditions for the optimality of binary quantizers. We have shown that when the observations are Gaussian, identical binary quantizers are optimal in the low SNR regime. For the location parameter estimation problem with a given prior distribution, we have found the optimal binary quantizer by solving a differential equation. We have found the sufficient condition on the noise distribution for which the threshold quantizers attain the performance limit. By relaxing the assumption of conditionally independent observations at the sensors, we also derived the optimality conditions for quantizers with conditionally dependent observations.

Reliable Crowdsourcing for Multi-Class Labeling Using Coding Theory

We have proposed the use of error-control codes and decoding algorithms to design crowdsourcing systems for reliable classification despite unreliable crowd workers [78]. Coding theory based techniques also allow us to pose easy-to-answer binary questions to the crowd workers. We considered three different crowdsourcing models: systems with independent crowd workers, systems with peer-dependent reward schemes, and systems where workers have common sources of information. For each of these models, we analyzed classification performance with the proposed coding-based scheme. We have developed an ordering principle for the quality of crowds and describe how system performance changes with the quality of the crowd. We also showed that pairing among workers and diversification of the questions help in improving system performance.

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1.

1. Report Type

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Organization / Institution name

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Grant/Contract Title
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Dynamic Information Collection and Fusion

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-10-1-0458

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Venugopal Veeravalli

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. Douglas Riecken

Reporting Period Start Date

08/16/2010

Reporting Period End Date

08/15/2015

Abstract

The project is aimed at developing a comprehensive framework for control of information collection, fusion, and inference from diverse modalities Our research has been organized under three inter-related thrusts. The first thrust addresses system modeling and local information processing. The second thrust emphasizes the interaction between information and control at different abstraction levels. The third thrust is focused on decentralized processing and interactive fusion. Within Thrust 1, we focused on exploring, developing, and utilizing mathematical models for hard and soft observations, the physical and abstract information states, and the sensing state for local information processing and inference. Within Thrust 2, we have obtained a number of results on sensor scheduling for target tracking, controlled sequential multihypothesis testing, controlled sensing for graph classification, universal outlier hypothesis testing, and optimal search and stop. Within Thrust 3, we have obtained a number of results on interactive fusion, data reduction with quantization constraints, network consensus and quantized alternate direction method of mutlipliers (ADMM), and resource management in sensor networks.

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Archival Publications (published) during reporting period:

[1] W. Ding, P. Ishwar, V. Saligrama, and W. C. Karl, "Sensing-aware Kernel SVM," in Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Florence, Italy, 4–9 May, 2014.

[2] M.H.Rohban, P.Ishwar, B.Orten, W.C.Karl, and V.Saligrama, "An Impossibility Result for High Dimensional Supervised Learning," in Proc.IEEE International Information Theory Workshop (ITW), Seville, Spain, 9–13 Sep., 2013.

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Changes in research objectives (if any):

None.

Change in AFOSR Program Manager, if any:

Dr. Tristan Nguyen was replaced by Dr. Douglas Riecken.

Extensions granted or milestones slipped, if any:

None.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
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Total			

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Appendix Documents

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